Mismatch Length Estimation of Self-Homodyne Coherent Optical Systems by Using Carrier-Pilot-Assist Method

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Abstract: The Self-Homodyne Coherent (SHC) is a promising solution for inter- or intra datacenter application in future. We proposed a carrier-pilot-assist (CPA) method to estimate mismatch length, which provides guidance for alleviating phase noise of SHC system. This method is robust and is independent of performance of DSP algorithm and IQ imbalance impairment.

1. Introduction

As the era of 5G time arrives, the deployment of application such as internet of thing, live streaming online and cloud computing services will gather pace. This will sharp tension of transmission bandwidth resource intra- or inter- datacenter needs. Different from long-haul optical transmission, the short-reach transmission needs to consider cost and power consumption. Thus, intensity modulation and direct detection (IMDD) is tended to use in intra- or inter- datacenter. However, due to limit of low chromatic dispersion (CD) tolerance [1], IMDD will hit a bottleneck on the way of arriving 800G or 1.6T of Ethernet interface data rate. The coherent detection will devolve to short-reach communication in future, which has become a consensus in the academic circles [2]. The coherent detection has advantage of high receiver sensitivity, high spectral efficiency, and fine CD tolerance. It also has mature structure and theoretical foundation in long-haul transmission. However, some modification needs to be done to meet demand of low cost and power consumption. The SHC system is proposed and considered as a promising coherent-lite scheme [3,4]. And some challenges such as tolerance of phase noise and polarization control have been clarified, which are needed to be overcome urgently. Among them, the impairment of phase noise induced by mismatch length between local oscillator (LO) path and signal path are acceptable when the product of linewidth and mismatch length is kept blow 0.18 MHz·m [5]. In this paper, we proposed a CPA method to estimate and adjust the mismatch length, which can be used to minimize the product.

2. Analytical Model

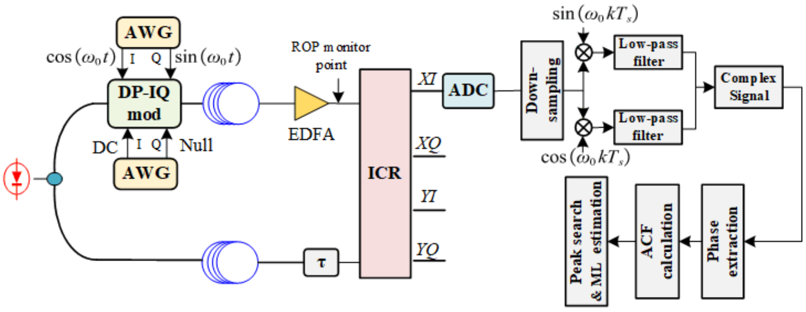

Figure. 1 Simulation setup and DSP offline of CPA estimation method by using SHC system

The schematic of mismatch length can be estimated by structure inherent SHC system subtly, as shown in Fig. 1. It's worth noting that remoted LO will induce power fading due to polarization state rotation in actual SHC system. Thus polarization control is essential. Here, we assume that this impairment has been compensated absolutely. In order to avoids noise in low frequency, the sinusoidal and cosine signals are used to shift the frequency. Besides, the light passes through IQ modulator without signal by imposing DC source in another polarization. The incident E-field before the photo-detector of ICR can be written in terms of the delayed and phase modulated signals for X polarizations:

$$E(t) = \frac{1}{2}[E_{CW}(t-\tau) - E_{CW}(t).e^{j\omega_0 t}] = \frac{1}{2}\left[e^{i(\omega_c(t-\tau)+\varphi_n(t-\tau))} - e^{i((\omega_0+\omega_c)t+\varphi_n(t))}\right] \quad (1)$$

where $\sqrt{P}$ represents the field amplitude, ω_c denotes the frequency, $\varphi_n(t)$ is the phase noise, τ is delay time induced by mismatch length of fibers between signal path and LO path, ω_0 is frequency of signal which provides driving voltages for in-phase or quadrature arms of IQ modulator. After photoelectric detection, the output current of X polarization from the BPD (balanced photodetector) with responsivity R is:

$$I_X(t) = \frac{RP}{2} cos[\omega_c \tau + \omega_0 t + \varphi_n(t) - \varphi_n(t-\tau)] \quad (2)$$

The phase difference $\varphi_n(t)$-$\varphi_n(t-\tau)$ can be marked with $\Delta\varphi(t)$. FM noise of $\Delta\varphi(t)$ can be obtained by operation of differentiation, namely difference in discrete time situation. Here, we denote it as FM(t). Then the PSD of FM(t) can be derived as

$$S_{FM}(f) = \frac{\Delta\nu}{2\pi}\left(2{-}2cos(2\pi\tau f)\right) \quad (3)$$

where $\frac{\Delta\nu}{2\pi}$ represents the PSD of FM noise of phase noise $\varphi_n(t)$, $\Delta\nu$ is linewidth of laser. According to Wiener-Shinchin theorem, autocorrelation function (ACF) can be obtained by doing inverse Fourier transform to $S_{FM}(f)$, as equation (4) expressed:

$$ACF(k) = ifft\left\{\left|fft\left(FM(n)\right)\right|^2\right\} \quad (4)$$

3 peaks will be observed easily in position of DC and ±τ [6]. Thus, the delay time τ and mismatch length can be found. Then engineer can adjust fiber length to realize carrier recovery free in DSP of Self-Homodyne Coherent Optical Systems. In order to assess the effect of OSNR on peak value, we introduce an index of PAR, which is defined as:

$$PAR = 10\log 10\left(|ACF_{\max}|/\sqrt{mean(|ACF(k)|^2)}\right) \quad (5)$$

Since we only observe negative peak, we calculate the PAR of negative ACF.

3. Simulation Results and Discussion

Based on schematic illustrated by figure 1, the simulation setup is built by using of MATLAB and VPI Transmission Maker. The sinusoidal and cosine digital signal with 5GHz of frequency is generated in Matlab. In the signal path, the optical beam passes through double polarization IQ modulator. The sinusoidal and cosine signal which have 100MHz of frequency are fed into arms of X- polarization. Then 10km fiber is used to transfer signal and LO. Finally, the beat signal after ICR is captured by ADC at sampling rate of 50 GS/s. After down-sampling, the sampling rate are denoted as 50/N(N=1,2,4,8). The signal captured is processed by DSP procedure as gray part of Fig.1 shows. The low-pass filter is used to make down-conversion and avoid high pass characteristic of differential operation. The pass-band edge frequency and stop-band edge frequency of low-pass filter are set as 450 MHz, 500 MHz respectively.

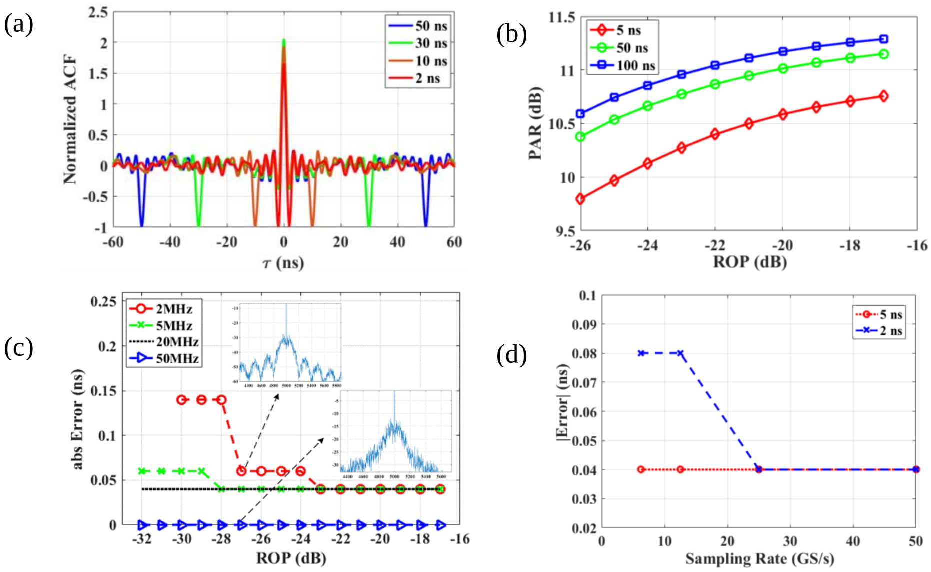

Figure. 2 (a)The normalized ACF versus delay time without low-pass filter (b) he PAR function of ROP (c) the error versus ROP, under different linewidths and delay time (d)The error function of sampling rate at 45MHz of laser.

We estimate the delay time when the delay line is set as 2ns, 10ns, 20ns, as figure 2(a) illustrates. The function of PARs as ROP are also measured in different delay time, as figure 2(b). The PAR will increase as increasement of delay time and ROP. However, 9.8dB is enough to distinguish peak for even -26 dBm of ROP and 5ns of delay time. Figure 2(c) shows that larger linewidth will improve accuracy measurement, which is be propitious to decrease of cost of SHC. The reason is that the main lobe of spectral width is related to delay time and immanent linewidth of laser in self-homodyne system (see insert of Figure 2(c)) [7]. Besides, we also investigate the effect of sampling rate on error as figure 2(d) shows. The accuracy is within the acceptable range when sampling rate equals to 10MS/s. This will provide guidance for experimental verification.

4. Experimental Verification

In order to test and verify the feasibility of scheme proposed, we conducted the experiment based on the structure of Figure 1(a). In the experiment, we use single polarization IQ modulator to substitute DP-IQ modulator, and the sinusoidal and cosine signal were injected to the two arms respectively. The field PSD of laser used is showed in Figure.3(a), which is up to 45 MHz. Besides, we only use 10m of optical fiber patch cord to delivery LO. And optical delay line is substituted by optical fiber patch cords which have length of 1m, 1.5m, 2m, 3m and 5m. Each length is measured 5 times. Before estimating the mismatch length, the fiber length difference induced by pigtail of instrument incidental between signal path and LO path is calibrated by same estimation method. It is worth mentioning that the OSC only captured signals of one output channel of ICR as sampling rate of 10GS/s， namely, XI or XQ component.

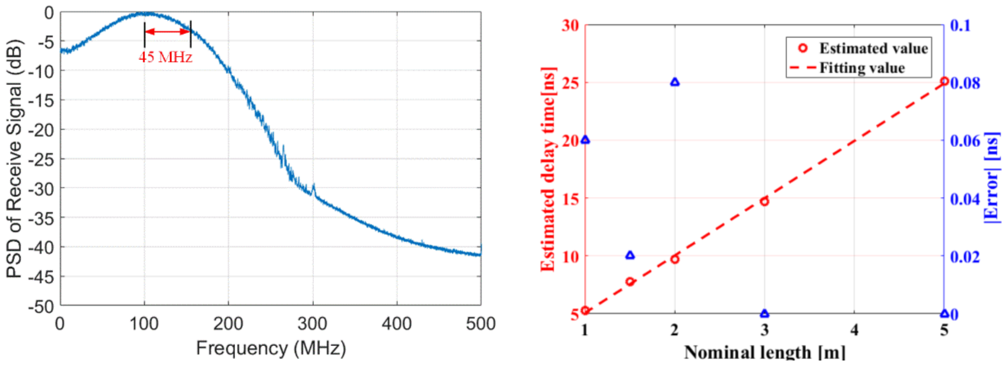

Figure. 3 (a) Block of DSP-offline in experiment (b) The average estimated delay time versus nominal length of patch cord. Red curves are fit results. The secondary axis shows error between fitting value and estimated value of each time.

The figure 3 (b) shows that average predicted value almost accords with what the fiber patch cord mark, which indicates our method is effective. The R^2 of fitting curve is 0.9988, which illustrates the curve fits well with average predicted value. The error between fitting value and average estimated value is showed in the secondary axis, which fluctuates from 0 ns to 0.08 ns.

5. Conclusion

A pilot-assist mismatch length estimated method is proposed and demonstrated in experiment for SHC system. This method is not affected by window length of carrier phase recovery algorithm and ROP. Besides, it also has strong robustness. This method will pave a promising pathway towards realization of SHC.

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